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SEISMIC DAMPING SYSTEMS WITH TMDS FOR HIGH RISE BUILDINGS

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Abstract

High rise buildings suffer from earthquakes mainly from rather big lateral displacements on top of 2m or more due to their long structural periods of 4-5s and even more. These displacements are acceptable if occurring for a view cycles during the earthquake. However the decay time of these vibrations after the earthquake can be up to 20 minutes as the structures have very low damping capabilities. These vibrations may induce low cycle fatigue resulting in cracking effects within the structure. To overcome this problem damping must be added to the structure.

In the past this was mainly achieved by diagonal bracing systems with hydraulic dampers, what often results – depending on the project and the seismic impact strength – in uneconomical solutions.

A more economic approach to reduce only the vibration decay times is the application of Tuned Mass Damper systems.

The aim of this paper is to introduce and describe the design and realization of two large TMD systems for high rise structures with their seismic function benefits:

- SOCAR Tower in Baku/Azerbaijan is 200m tall and has a 450t mass double pendulum type TMD with passive damping, and
- Danube City (DC) Tower in Vienna/Austria is 220m tall and has a 300t mass single pendulum type with semi-active damping, which is adopting in real time its damping capability.

Both TMD systems have in addition redundant end stopper devices to avoid uncontrolled seismic displacements of the huge TMD mass blocks.

Keywords: Damping, Tuned Mass Damper (TMD), seismic control, semi-active

1. Introduction

Tall structures have considerably low natural frequencies and are relatively soft which may result in significant lateral deformations on the roof top when exposed to earthquake or wind. While vibrations caused by regular wind occur frequently and may make us feel uncomfortable, earthquake or extreme storm events may not happen often but when happens it may damage the structure. Extreme and moderate load cases lead to different optimum protection needs. And, if a structure has to be protected from both service loads like wind and ultimate loads like earthquake/storm, a protection against ultimate load cases alone will neglect the demands caused by regular wind or other live loads. For example, an optimum protection system against earthquake will be unsuitable to mitigate vibrations caused by frequent service loads, and for optimum tuning in service stage we end up with an unprotected structure for ultimate load cases while exposed to increased fatigue effects. Therefore an effective damping system – like a TMD system - must be installed in soft structures to avoid cracks, fatigue or even comfort decrease.

A main goal of a TMD system within tall structures is to increase damping to reduce accelerations and displacements to avoid fatigue effects and/or even increase the comfort. The TMD system must be perfectly adapted to the structural frequency, structural mass, wind or seismic input parameters and it must act differently depending on the occurring load cases or intensity levels, respectively. Therefore the system must be able either in a passive mode or in a controlled mode to adopt within certain compromises or even without compromises to occurring real site conditions. Only then it can provide the technically necessary additional damping within an economical frame work.

2. Basic requirements for TMD systems in tall structures

2.1 General considerations

In case a structure has to be protected against ultimate loads due to earthquake or severe storm events, usually it is expected from a TMD system that it is properly damping for service loads (wind, live loads), too. Depending on the chosen mass ratio, which is the TMD mass in relation to the modal mass of the first structural mode, the TMD mass will do more or less horizontal relative movement in relation to the structural mass. This relative movement is also finally depending on the specified regular wind (time history), storm (impact force) and earthquake (response spectrum) input parameters. The TMD mass is set onto the roof top of the tall structure, as there the structural displacements for mode 1 are most significant and it can work most efficient. The TMD mass is a secondary mass which is reacting already on extremely small lateral roof top vibrations even less than 5 mm and it is reacting with extreme amplitudes in case of earthquake. Therefore the TMD mass must be designed to allow the required displacements amplitudes and possibly provide an end stopper or snubber system to have control over the often huge TMD mass at any time. These relative movements of the TMD mass are laterally damped towards the structure by a hydraulic damper unit what results with the out of phase movement of the TMD mass in additional reliable structural damping [1].

Instead of a TMD system sometimes a diagonal bracing or outrigger system with integrated friction or hydraulic dampers have been applied. These systems get properly activated only when significant displacements within the dampers of at least 10-20 mm occur. To generate these displacements at the damper locations the structure would have to move on top by at least 0.5 m or even more. Thus the displacements at the damper locations often do not even occur for the maximum seismic event and also not for regular small service vibrations of the structure. However without movement no additional damping will be provided by the hydraulic dampers what results in an increase for structural vibrations and an extended decay period for structural vibrations, possibly even in structural damages. Therefore bracing dampers can be good for MCE events, acting like the last line of defense to avoid structural collapse or major structural damages but they are usually not much suitable to avoid cracks due to fatigue effects and are not able to increase the comfort for structures with long periods. Therefore it is very important that the designer defines the demand for a damping system, which has then to be chosen according to these requirements together with the supplier.

2.2 Direction of damping

Since the direction of the attack, i.e. the energy input into the structural system with corresponding dynamic forces, might come from any horizontal direction, but a high rise structure usually is not symmetrical, the natural frequencies of vibration are different in X-direction as compared to Y-direction. Consequently, different damping amounts have to be devised. Ideally, just one TMD system should suffice that adapts to the various occurring frequencies to be damped in specific directions.

2.3 Low cycle fatigue effects

Low cycle fatigue can occur when an earthquake triggers large lateral displacements in the upper stories of high rise buildings which, when not damped, can lead to long-period motions of 20 minutes and longer. [2] and [3] report cases of long distant earthquakes which induced long-period motions within (not damped) high-rise buildings. A TMD system will shorten this period to 15-40 s, preventing low cycle fatigue especially within the valuable facade. The TMD system will increase durability of the entire structure then.

2.4 Required internal viscous damper characteristics

The TMD system consists of certain hardware like internal viscous dampers connecting the TMD mass with the structure, a tuned mass, steel frames, pendulum system, brackets & guides, semi-actively controlled dampers (optional), monitoring, etc.. These single components of the TMD system must be suitably designed and perform with certain criteria.

For example, a high friction coefficient within a mass guide system or high damping performance within the hydraulic damper to ensure a superior energy dissipation in case of earthquake will prevent relative displacements of the TMD mass in case of lower but frequently occurring service loads. Then the entire TMD system will be unsuitable for protection in service stage. This phenomenon is called back ground friction, what is the internal friction of a TMD system. In case this friction, especially considering the frequently occurring service load cases, is too high, the TMD system will not even be triggered. It behaves like a stiff structural member, and mitigation of vibration will not work. Ideally, the back ground friction has to be kept so low that for example the damping within a tuned mass pendulum damper can be triggered for frequent service load cases at a horizontal acceleration of 0.01 m/s2, which is even below the threshold of people feeling it.

The response force of a viscous damper within a TMD system follows the formula

$$F = C \cdot v^{\alpha} \tag{1}$$

Whereby F is the response force, C is an individually chosen damping constant, v is the velocity of the piston, and α is the damping exponent.

This exponent α and the damping constant C are of critical importance and have to be chosen individually for service and seismic load cases. Usually the damping exponent is linear viscous ($\alpha = 1$) to achieve proportional force-velocity behavior gaining optimal damping performance, i.e. for instance to satisfy Den Hartog criteria for service conditions. However for the seismic load case it is desired that the damping constant C will increased to provide greater energy dissipation and effective control or limitation of the maximum TMD mass displacements.

2.5 Space restrictions

Usually the space on top of a high rise building is constrained as it is very valuable. A TMD damping system must fit to the given small geometrical constraints, what must result in special adaptations of steel works, dampers and other devices within the TMD system to effectively shrink it. Therefore the systems often have special designs like double or inverted pendulum solutions.

2.6 Controlled TMD system

A controlled TMD system has semi-actively controlled hydraulic dampers [4 & 5] inside, which are able to create hysteretic loops with a positive or negative slope (Fig. 1). In addition the volume or energy dissipation respectively of the hysteretic loop can be controlled within 10 % to 100 % in real time, too (Fig. 2).

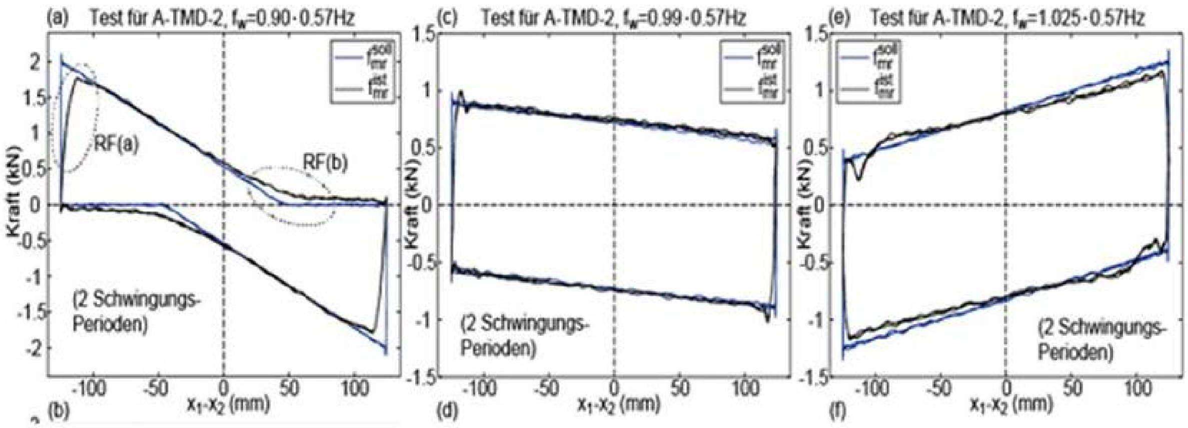

Fig. 1 - Positive and negative stiffness within hysteretic loops of semi-actively controlled

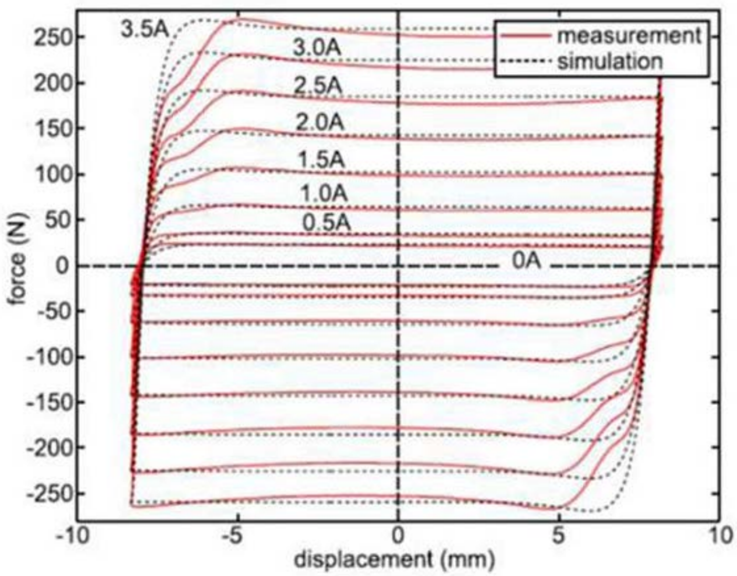

Fig. 2 - Hysteretic loops of semi-actively controlled damper depending on degree of force control

The input signal for the control is coming from an acceleration sensor in the structure, which is converted within an electronic unit with a special control algorithm into an output signal controlling the magnetic valve of the controlled damper. This allows to adapt the damping constant C in real time according to the required performance level and the damper adjusts itself to any vibration amplitude of the tuned mass. Even in case the structural frequency changed during the service life time the controlled TMD will change within +/- 15 % the TMD system frequency accordingly. The function of these semi-actively controlled hydraulic dampers was excessively tested at the EMPA Switzerland and the results are shown in Fig. 1 & 2. This controlled system is absolutely fail safe, as in case the electricity supply fails, the dampers will fall back into a predetermined passive mode, which would be the one chosen in case a passive TMD system would have been applied.

A monitoring system for frequency, acceleration, displacement, forces, etc. can be easily installed and provide in real time an efficiency check of the TMD system together with all relevant interesting function checks.

2.7 Commercial aspects

A structural protection system with TMDs usually has to be considered with less than 1 % of the total cost of the structure. These costs do not necessarily come “on top” of the costs of the structure, but can partially or even fully be recovered by the savings that a TMD system will entail. For example, not to procure a TMD system will possibly have as a consequence that the accelerations in a structure translate into greater forces or bending stresses respectively, which requires more material to increase structural stiffness and resistance for the safe transfer of these greater forces and to avoid fatigue in structural members. It could already be demonstrated that in certain projects the savings in reinforcement steel alone were bigger than the costs of the procurement of a TMD system.

Insofar care has to be taken when comparing costs of TMD systems of various suppliers. Often the more expensive smaller and efficient TMD system may be finally the cheaper one, because the consequential savings in the structure by far outweigh the additional costs when selecting a technically more sophisticated and smaller TMD protection system.

3. Case Studies

3.1 SOCAR Tower in Baku, Azerbaijan

The SOCAR Tower (Fig. 3) is the head office of the State Oil Company of Azerbaijan Republic (SOCAR), a 200 m tall office building which shall be protected against earthquake motions and wind induced sway motions by means of a tuned mass damper pendulum system.

Fig. 3 - SOCAR Tower in Baku

The designer provided performance requirements for a Tuned Mass Damper (TMD) with 450 t mass placed on the top of the tower which were quite challenging. The applied mass ratio of approx. 4.5 % will provide a maximum damping ratio of 7.4 % for service and ultimate seismic load cases. Even for the seismic load case the decay time for the structural vibration will be in the range of less than 1-2 minutes.

From a requested frequency of 0.16 Hz and thus a period T of 6.25 s, and solving the Eq. (2)

$$T = 2\pi \, \mathrm{sqrt}\,(L/g) \tag{2}$$

The length L of the pendulum would calculate to approx. 9.7 m then.

This is, considering the spatial allowed constraints, too long or results in a too tall single pendulum TMD design respectively. This single pendulum TMD would have not fit into the quite narrow roof top.

So the total pendulum length L was split into two sections l_1 and l_2, resulting in a double pendulum displaying the very same characteristics of the natural frequency to be damped, namely 0.16 Hz (Fig. 4).

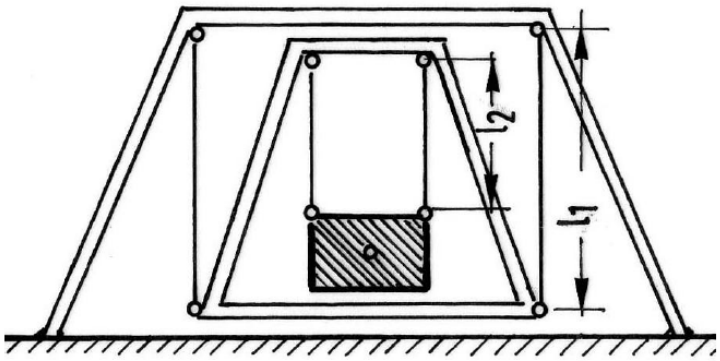

Fig. 4 - Principle Sketch of a double pendulum TMD.

In order to swing in different periods in horizontal X- and in Y-direction, the length of the very same pendulum must be different. This characteristic is achieved by way of a cable clamp which fixes the pendulum in a predefined but adjustable location. The pendulum can slide along its full length in the plane, along a sliding plate (Fig. 5). Perpendicular to this plane, the pendulum length can be shortened. The location of this “grip” into perpendicular direction can be adjusted allowing independent frequency control in X- and Y-direction.

Fig. 5 - Double pendulum steel frames with sliding fixation shoe for various pendulum frequency adjustments in X- and Y-direction.

If the pendulum cannot be tuned exactly to the real natural frequency of the structure, the damping is suboptimal. Here, this tolerance of less than 0.01 Hz is a function of the spacing of the fixations for the grip in perpendicular direction.

To limit for the earthquake the TMD mass displacement to max. +/- 500 mm visco-elastic lead rubber bearings (LRB) on top and bottom of the TMD mass where applied as end stopper in any lateral direction. The total maximum induced lateral forces within the LRB end stopper system are in the range of 1000 kN combined with 100 mm shear deformation while assuming 0.45 g PGA.

3.2 Danube City Tower in Vienna - Austria

With a height of 220 m and comprising 60 nos. stories the Danube City Tower 1 (Fig. 6) is the tallest building in Austria.

Fig. 6 - Danube City Tower 1

The applied TMD system was specified to be at top floor level with a controlled system of semi-actively controlled hydraulic dampers [4 & 5] to be incorporated into the single pendulum TMD system. The damper and guide system is placed between TMD mass and the structure (Fig. 7 right).

The requirement is to reduce accelerations caused by earthquake and regular wind. This meant that the very same damper shall be optimally effective for both the service stage (i.e. wind loads) with minor force response and the ultimate stage (i.e. earthquake) with major force response. Thus each stage will result in a different optimum damping demand. The tuned mass was specified to be 300 t hanging at bottom of a 6.88 m long single pendulum with steel cables, what reflects 0.75 % mass ratio. For this case the 300 t mass not only functions as a TMD mass, but also as a container for the fire fighting water (Fig. 7 left).

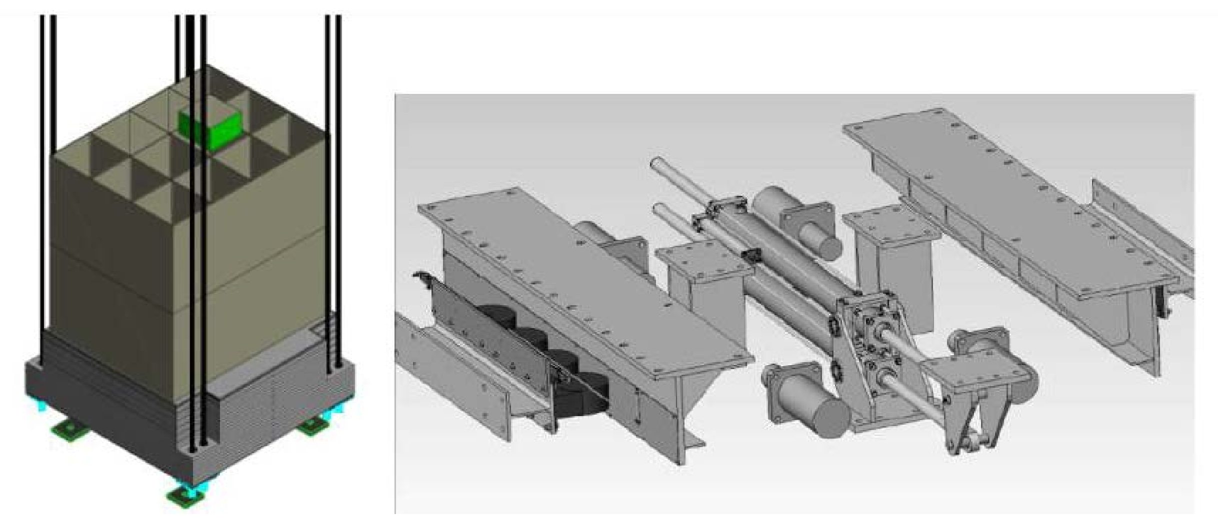

Fig. 7 - Single pendulum hanging on steel ropes with mass consisting of steel plates at bottom and $53m^3$ water container on top (left); guide-damper system under the mass (right)

The seismic structural analysis with 5% damping ratio in the hydraulic dampers within the TMD system brought about horizontal TMD mass vibration amplitudes of +/- 2 m considering seismic lateral accelerations of the ground of approx. 0.1 g. These amplitudes are not acceptable as the space conditions are not allowing such huge displacements. After increasing the damping ratio of the hydraulic damper to a level of 18 % the TMD mass amplitudes could have been reduced to +/- 620 mm, what is within the acceptable limits. In Fig. 8 with the amplitude-time plot it can be seen that after 20 s the structure shows no significant vibrations anymore. Therefore low-cycle fatigue will not occur at all due to long vibration periods after regular earthquakes. Fig. 8 clearly shows the out of phase movements of the TMD mass relative to the structure, i.e. the structure spends "energy" to let move the TMD mass, what is finally bringing additional damping to the structure. The TMD mass, which is rather small in relation to the structural mass, is and must always move more than the structural mass what is depending on the chosen TMD mass size or mass ratio (= TMD mass versus modal mass of structure for the mode to be damped) respectively. This is creating a more or less big delta amplitude between TMD and structure.

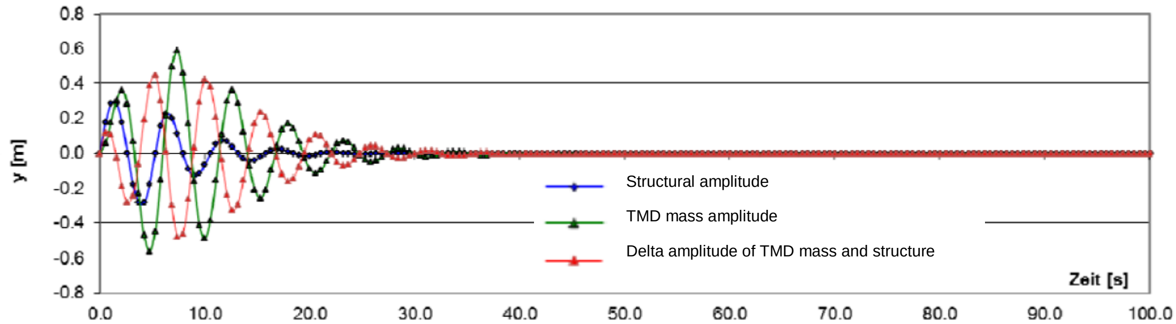

Fig. 8 - Amplitude-Time plot for 10s massive seismic excitation period and decay of structural vibration

In case of an earthquake, the main focus was on the protection of the structure while limiting the TMD mass displacements within +/- 750 mm and avoiding significant impact forces. The two controlled dampers will provide an increased damping of $\xi \approx 18$ % for earthquake only while significant energy dissipation with 270000 J will occur for +/- 750 mm TMD mass amplitude. This energy will be mainly dissipated within 550 mm and 750 mm amplitude with a maximum active viscous damper force of 470 kN on each of the four devices.

For regular wind loads at the top of the structure a not acceptable acceleration of up to 0.18 m/s^2 may occur without a TMD system. For these load cases the damping will be controlled within 2 % to 5% allowing maximization of the comfort for the people with accelerations less than 0.06 m/s^2. These in real time adaptive damping amounts result in an efficiency increase for the comfort criteria of up to 60 % compared to a regular passive system. Or in case the same performance like for a passive system was expected, the TMD mass of the semi-actively controlled system could have been reduced by approx. 20% (60 t less).

The installation of the semi-actively controlled damping system within the TMD of DC Tower 1 facilitates the installation of a monitoring system, which also was implemented. At any given point in time, the web-based password (Fig. 9) and protected monitoring system will display the temperature, displacement of the pendulum (amplitude), the response force of the viscous dampers and its current supply, and the natural frequency of the structure.

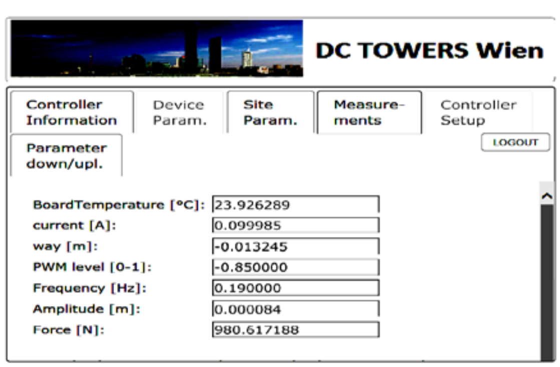

Fig. 9 - A real time screen shot of the recent measurements of the monitoring system

4. Conclusions

Elegant structures which are prone to vibrations and deflections shall be optimally protected for the maximum credible earthquake level and for the service load cases (e.g. wind). For the earthquake load case the focus is on avoiding damages and safeguard continued functionality – especially due to low cycle fatigue effects. For the service wind load cases it must be avoided that people feel sea sick or comfort is decreased to a not acceptable level. Custom made passive or semi-actively controlled single, double or inverted compact TMD systems are the tools to achieve such optimum structural protection, being even commercially viable by reducing overall construction costs.

The TMD system for any structure must be seen in four stages.

A – Proper design for the seismic load cases and possibly on demand for service load cases with small size to reduce structural costs and even gain money from more free space.

B – Economic durable design of the TMD system hardware for a long service life time.

C – Easy and quick installation on site as the time windows for installation are strictly limited for high rise structures.

D – Commissioning with final easy TMD system tuning on site according to real recorded structural frequencies.

5. Acknowledgements

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